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Changes in the red giant and dusty environment of the recurrent nova RS Ophiuchi following the 2006 eruption

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ABSTRACT

We present near-infrared spectroscopy of the recurrent nova RS Ophiuchi (RS Oph) obtained on several occasions after its latest outburst in 2006 February. The 1–5 μm spectra are dominated by the red giant, but the H I, He I and coronal lines present during the eruption are present in all our observations. From the fits of the computed infrared spectral energy distributions to the observed fluxes, we find $T_{\rm eff} = 4200 \pm 200$ K for the red giant. The first overtone CO bands at 2.3 μm, formed in the atmosphere of the red giant, are variable. The spectra clearly exhibit an infrared excess due to dust emission longward of 5 μm; we estimate an effective temperature for the emitting dust shell of 500 K, and find that the dust emission is also variable, being beyond the limit of detection in 2007. Most likely, the secondary star in RS Oph is intrinsically variable.

Key words: binaries: symbiotic – circumstellar matter – stars: individual: RS Ophiuchi – novae, cataclysmic variables – infrared: stars.

1 INTRODUCTION

RS Ophiuchi (RS Oph) is a recurrent nova (RN) with at least six recorded outbursts, in 1898, 1933, 1958, 1967, 1985 and 2006 (Wallerstein 2008). The system consists of a massive white dwarf (WD) and a red giant (RG) (Fekel et al. 2000). Like classical novae, eruptions are caused by a thermonuclear runaway (TNR) in material accreted on the surface of the WD (Starrfield, Sparks & Shaviv 1988), although it is unclear if the accretion disc is fed by Roche lobe overflow or the RG wind (Starrfield 2008).

Recurrent novae (RNe) are divided into subclasses, depending on the nature of the secondary star (Webbink et al. 1987). During eruptions in RNe with a RG secondary (like RS Oph), the ejected material runs into the RG wind, which is shocked. Broad emission lines arise in the shocked wind and ejecta, which narrow with time as the ejecta decelerate (Das, Banerjee & Ashok 2006; Evans et al. 2007a). In outburst, the infrared (IR) spectrum is dominated by these lines, and by free–free radiation (Evans et al. 2007b). In quiescence, the IR spectrum is dominated by the RG.

Dust emission was detected within three years of the 1967 eruption by Geisel, Kleinmann & Low (1970) and in 1983 by the *InfraRed Astronomical Satellite* (*IRAS*) survey (Schaefer 1986). More recently, Evans et al. (2007b) detected silicate dust features ∼7 months after the 2006 outburst; they concluded that the dust survives from one eruption to the next, and that some of the RG wind is shielded from the shock and ultraviolet (UV) blast from the outbursts.

Knowledge of the elemental abundances in the atmosphere of the RG is important for understanding the eruption, because the TNR on the WD occurs in material accreted from the RG secondary. Pavlenko et al. (2008) modelled a 2006 August spectrum of RS Oph in the 1.4–2.5 μm range and determined the following parameters for the RG: $T_{\rm eff} = 4100 \pm 100$ K, $\log g = 0.0 \pm 0.5$,

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Table 1. Observing log, best-fitting parameters and CO $\upsilon = 2 \rightarrow 0$ band depth as a percentage of the continuum.

UT date (1)	JD[a] (2)	t (d)[b] (3)	Telescope (4)	Φ^c (5)	f^d (6)	$T_{\rm eff}$ (K) (7)	$T_{\rm d}$ (K) (8)	CO per cent (9)
2006 August 1	3948	170	IRTF	0.33	0.16	4200	500	35
2006 August 9	3956	178	UKIRT	0.34	0.18	4200	500	34
2006 August 25[e]	3972	194	UKIRT	0.38	0.26	4200	500	27
2006 September 18[e,f]	3996	218	UKIRT	0.45	0.40	4200	400	31
2007 June 1	4252	474	IRTF	0.99	0.52	4400	—	26
2007 June 11	4262	484	UKIRT	0.01	0.48	4200	—	22
2007 July 28	4309	531	IRTF	0.12	0.26	4400	—	20
2008 July 15	4662	884	UKIRT	0.89	0.72	4000	500	27

[a]Julian date – 245 0000.
[b]$t = 0$ is 2006 February 12.85
[c]Orbital phase calculated from Fekel et al. (2000).
[d]Fraction of visible RG surface irradiated by WD.
[e]Data in Pavlenko et al. (2008).
[f]IJ to L′ on this date, M on 2006 September 19.

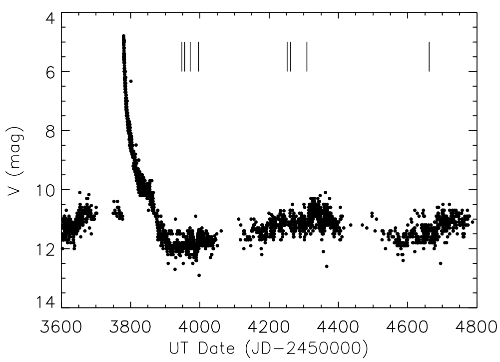

Figure 1. The visual light curve of RS Oph from the American Association of Variable Star Observers (AAVSO), covering the 2006 outburst. The vertical lines show the dates of our observations.

[Fe/H] = 0.0 ± 0.5, [C/H] = −0.8 ± 0.2 and [N/H] = +0.6 ± 0.3. These abundances may vary considerably, however, if the RG is contaminated by the nova ejecta, as has been suggested by Scott et al. (1994). Irradiation of the RG by the still-hot WD may also be a complicating factor in the immediate aftermath of an eruption.

The latest outburst of RS Oph was discovered on 2006 February 12.85 UT (Hirosawa 2006); we assume the eruption began on this date ($t = 0$). IR spectra from the first 100 days of the outburst are discussed by Evans et al. (2007a,b), Das et al. (2006) and Banerjee, Das & Ashok (2009).

Here, we present IR spectroscopy of RS Oph obtained on later dates and at different orbital configurations. We investigate the effects of irradiation on the secondary and dust emission at longer wavelengths.

2 OBSERVATIONAL DATA

An observing log is given in Table 1. Fig. 1 shows the times of our observations with respect to the visual light curve of RS Oph.

2.1 UKIRT

IR spectroscopy of RS Oph was obtained at the United Kingdom Infrared Telescope (UKIRT), with the UKIRT 1–5 μm Imager Spectrometer (UIST) (Ramsay et al. 2004). The observations were obtained in stare-nod-along-slit mode, with a two-pixel-wide slit. We obtained data in the *IJ* (0.86–1.42 μm), *HK* (1.40–2.51 μm), short *L* (2.91–3.64 μm), long *L* (3.62–4.23 μm) and *M* (4.38–5.31 μm) band grisms, giving a spectral coverage of 0.86–5.31 μm. The resolving power is ∼600–2000. We obtained spectra of HR 6493 (F3 V) immediately before we obtained spectra of RS Oph, for calibration purposes.

The data reduction method followed the usual routines for IR spectra. The data at one nod position were subtracted from data at a second nod position to remove sky emission lines, and the sky-subtracted data were extracted from the UIST array. The extracted spectra of RS Oph were divided by the extracted spectra of the standard star to remove telluric absorption. The target was observed at a similar airmass as the standard star to optimize the cancellation of these features. The ratioed data were then multiplied by a normalized blackbody to provide flux calibrated spectra; this assumes the spectrum of HR 6493 is a 6700 K blackbody, with $K = 3.6$ (Tokunaga 2000). The data were wavelength-calibrated using the spectra of arc lamps and telluric lines in the standard star data.

2.2 IRTF

Observations were made using SpeX (Rayner et al. 2003) on the NASA Infrared Telescope Facility (IRTF)[1] in double-beam mode. The slit dimensions were 0.8 × 15 arcsec^2 and the nod was 7 arcsec along the slit. The resolving power is $R \sim 700$–900. To minimize atmospheric dispersion, the parallactic angle was set such that the slit was oriented vertically. Internal wavelength calibration and standard star observations were interspersed between spectra of RS Oph. In all cases, the star HD159170 (A5V) was used as a standard, and was within 0.07 airmass of RS Oph. All data were reduced with SPEXTOOLS (Cushing, Vacca & Rayner 2004). To generate the flux model for the standard star, we took the spectral type and measured colour ($B - V$), and then scaled Kurucz' model spectra (Kurucz 1994; Kurucz & Bell 1995) to the V flux.

[1] Data obtained by visiting astronomers at the Infrared Telescope Facility, which is operated by the University of Hawaii under Cooperative Agreement no. NCC 5-538 with the National Aeronautics and Space Administration, Science Mission Directorate, Planetary Astronomy Program.

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2.3 Orbital phase

The orbital phase of RS Oph (Φ, defined such that maximum radial velocity of the RG occurs at Φ = 0.00) at the time of our observations is shown in Table 1 (phase at $t = 0$ is Φ = 0.95), and was calculated from the orbital period and a zero phase reference (Fekel et al. 2000). In Table 1, we also show the visible fraction of the RG hemisphere irradiated by the WD at the time of the observations, assuming inclination 50° (Brandi et al. 2009 derive $i = 49°–52°$; Dobrzycka & Kenyon 1994, $i = 30°–40°$; and Ribeiro et al. 2009, $i = 39 \pm ^{1}_{10}$).

The spectra presented in this paper are dereddened using $E(B - V) = 0.73$ (Snijders 1986).

3 RESULTS

3.1 Model fits to observed spectra

IR spectra of RS Oph in the range 0.9–2.4 μm are shown in Fig. 2. They contain the H I, He I and coronal emission lines reported in earlier spectra by Evans et al. (2007a,b) and Evans et al. (in preparation). These lines originate in the shocked wind and gradually fade from the data. Evans et al. (2007a) report early 2006 IR spectra, when the continuum is dominated by emission from the hot gas. The earliest spectra reported here are from 2006 August. By this time, the emission from the gas had subsided and the RG dominates the IR spectrum. Besides emission lines from the shock, the spectra in Fig. 2 contain absorption features from the secondary; these are the subjects of this paper.

Photometry of RS Oph shows that the V flux declined below the pre-outburst value and reached a minimum ∼200 d after maximum. The V flux rose thereafter, reverting to the quiescent level after about 400 d (Darnley, Hounsell & Bode 2008). IR photometry during eruption has been published for the 1985 outburst (Evans et al. 1998) and (for a more limited time-base) by Banerjee et al. (2009). These data show that the behaviour in the IR is similar to the behaviour in the optical. In our data, the pre-outburst flux is essentially recovered by $t = 474$ d.

The IR continuum and absorption spectrum of RS Oph have been analysed with a spectral synthesis technique, using $\log g = 0.0 \pm 0.5$, [Fe/H] $= 0.0 \pm 0.5$, [C/H] $= -0.8 \pm 0.2$ and [N/H] $= +0.6 \pm 0.3$ (see Pavlenko et al. 2008, for more details), and microturbulent velocity $V_t = 3\,\mathrm{km\,s^{-1}}$ (Pavlenko et al. 2009). Contributions of the various molecular and atomic species to the total opacity are shown in Fig. 3. The strongest molecular absorption is from the CO first overtone ($\Delta\upsilon = 2$, where υ is the vibrational quantum number) and the CN red system ($A^2\Pi - X^2\Sigma^+$). As well as these features, a broad emission peak at 1.6 μm, which is observed in late-type stars, is present in RS Oph and is due to the minimum in the H^- bound–free and free–free opacity (John 1988).

The best-fitting model parameters are given in columns 7 and 8 of Table 1 for the dates of observation. Most fits were obtained with the best-fitting parameter $T_{\rm eff} = 4200 \pm 200$ K. The values $T_{\rm eff}$ in Table 1 are essentially the same within the uncertainties.

We note that the model is unable to fit all parts of the data. The largest discrepancy is seen in 2007, around the H^- opacity minimum. This problem is apparent in all data, but it is more acute in 2007 (see Fig. 4). The peak due to the H^- minimum is absent from these spectra, implying a change in the IR spectrum of the RG.

Further evidence of a change in the RG can be seen in Fig. 5. In this figure, the CO first overtone bands are shown in all our UKIRT data. Bands from ^{13}CO, as well as the main isotopomer, ^{12}CO, are present (the isotopic ratio ^{12}C/^{13}C for the RG is ^{12}C/^{13}C $= 22 \pm 3$; (Pavlenko et al. 2009). The CO absorption is clearly weaker in the 2007 data than it is in the other data. The CN bands may also be weaker, but the change is less pronounced than it is in the CO. The

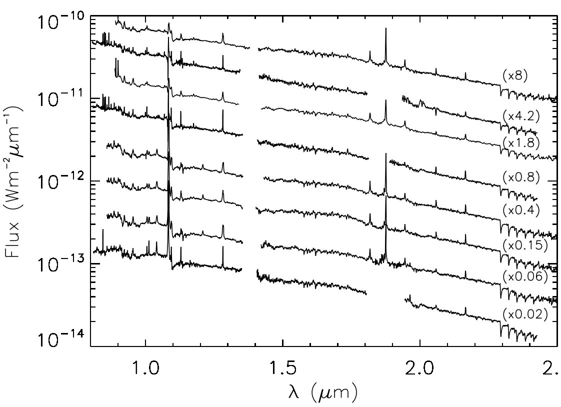

Figure 2. Near-IR spectra of RS Oph in the 0.8–2.5 μm range. From bottom to top, the observing dates (UT) are 2006 August 1, 2006 August 9, 2006 August 25, 2006 September 18, 2007 June 1, 2007 June 11, 2007 July 28 and 2008 July 15. The data have been multiplied by the amounts in brackets to vertically offset for clarity. The spectra have been dereddened using $E(B - V) = 0.73$ (Snijders 1986).

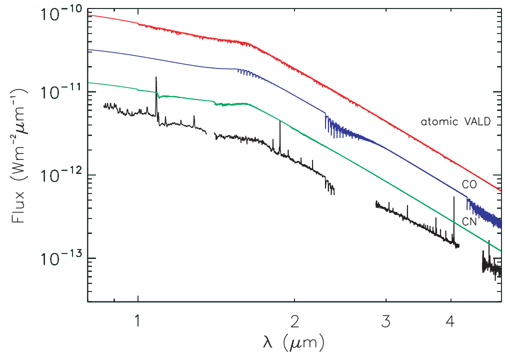

Figure 3. Computed spectra showing the ^{12}CO, ^{13}CO, CN and atomic contributions to the observed data (bottom spectrum). The computed spectra are shifted vertically to aid comparison. The emission lines following the eruption are still present in RS Oph.

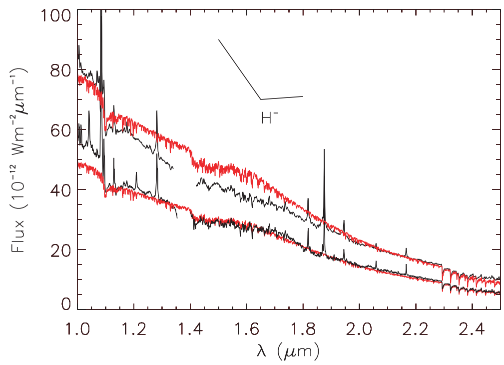

Figure 4. Best-fitting models (red) to the RS Oph data on two dates (black); the bottom spectrum is from 2006 August 25 and the top spectrum is from 2007 June 11. A large discrepancy between the model and data is apparent in the 1.2–2.0 μm range on 2007 June 11. The wavelength range of the minimum in the continuous absorption coefficient of the negative hydrogen ion is shown above the spectra.

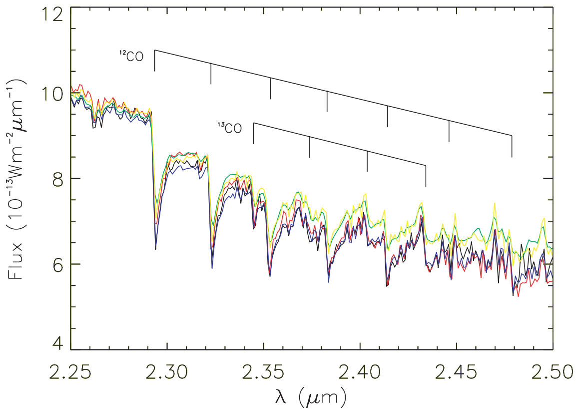

Figure 5. CO first overtone bands in RS Oph at $R = 2000$. Observation dates (UT) are 2006 August 9 (*black*), 2006 August 25 (*red*), 2006 September 18 (*blue*), 2007 June 11 (*green*) and 2008 July 15 (*yellow*). The spectra have been vertically shifted to the level of the 2006 August 9 spectrum to aid comparison. The vertical lines show the positions of the ^{12}CO and ^{13}CO vibrational band heads. The CO absorption is weaker on 2007 June 11 than it is on the other dates.

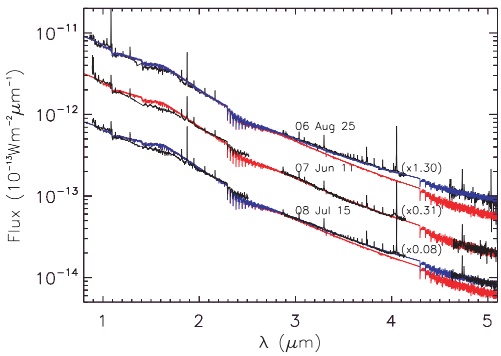

Figure 6. Model fits to the observed data (black lines) over the 0.8–5 μm range. From top to bottom, the observation dates (UT) are 2006 August 25, 2007 July 11 and 2008 July 15. The red lines are model atmosphere fits, the blue lines are fits obtained by the addition of a 500 K blackbody to the model atmosphere. The flux in the model drops below the flux in the data in the $\lambda > 3$ μm region in the 2006 and 2008 data. This IR excess is due to emission by dust. The data have been multiplied by the amounts in brackets to vertically offset for clarity.

strength of the CO $\upsilon = 2 \rightarrow 0$ band is shown in column 9 of Table 1 as a percentage of the continuum, from which it can be seen that the absorption is weakest on 2007 July 28. Possible reasons for the behaviour of the CO are given below.

3.2 The dust continuum

Fig. 6 shows the best-fitting model to the data on 2006 August 25, 2007 July 11 and 2008 July 15 over the 0.8–5 μm range. The flux in the model falls below the flux in the data for wavelengths $\gtrsim 3$ μm: RS Oph clearly exhibits an IR excess. There are two possible explanations for this excess: free–free radiation and dust emission.

Evans et al. (2007b) reported the appearance of the silicate features at 9.7 and 18 μm in *Spitzer* data between 2006 April and September. They concluded the dust was present before the outburst, that hot gas emission masked the dust emission in the earlier data, but as the emission from the gas subsided, the silicate features were revealed. Since free–free emission had faded by late 2006, and the silicate features were observed at this time, dust is the likely source of the excess in our data.

van Loon (2008) used the DUSTY code to model the *Spitzer* spectrum and found a dust temperature of 600 K. From his fit, we find the dust contributes $\sim 7 \times 10^{-14}$ W m^{-2} μm^{-1} at 4 μm, approximately 50 per cent of the flux in our 2006 data, and 40 per cent in our 2008 data.

Since the contribution is significant at the longest wavelengths in our data, and the dust emission peaks longward of ∼5 μm, we use a blackbody in our computations to mimic the dust emission: the effect of a ν^{β} dust emissivity law on the Wein tail is not expected to be significant. The inclusion of a blackbody greatly improves our fits to the 3–5 μm region for all but three spectra: 2007 June 1, 2007 June 11 and 2007 July 28; the dust emission is at least a factor of 3 weaker in 2007. Fig. 6 shows the dust excess on 2006 August 25, its absence on 2007 June 11 and its presence again on 2008 July 15.

The dust temperatures ($T_{\rm d}$) are given in column 8 of Table 1. The uncertainty in $T_{\rm d}$ is at least ±100 K because of the absence of data at $\gtrsim 5$ μm, where the dust emits most strongly and dominates the continuum. The temperature of the dust is consistent with that in van Loon (2008), and the dust contribution is consistent with an extrapolation of the *Spitzer* fluxes. Therefore, we are confident that the excess we see is emission from the dust detected by Evans et al. (2007b). These observations therefore support the claim that the dust will be present at the next eruption (Evans et al. 2007b).

As already noted, the 2007 spectra are unusual and are further discussed below; we note that these data were obtained at both UKIRT and IRTF, so there is no doubt that the effect is real and not instrumental or an artefact of data reduction.

4 DISCUSSION AND CONCLUSIONS

4.1 CO

In this paper, we have presented IR spectroscopy of RS Oph obtained on eight occasions after the 2006 outburst, starting on $t = 170$ d and ending on $t = 884$ d. Although the values of effective temperatures on all observing dates are generally consistent, we see changes in the spectral features from the RG, the most obvious being a significant weakening of the CO first overtone bands. We now consider possible explanations for this behaviour.

The weakening of the CO first overtone bands in RS Oph has been observed before, following the 1985 eruption. Scott et al. (1994) obtained IR spectroscopy of RS Oph in quiescence in 1992. The strength of the CO absorption features had declined significantly from an observation 7 years earlier, 143 days after the 1985 outburst (Evans et al. 1998). Harrison, Johnson & Spyromilio (1993) obtained IR spectra of RS Oph in 1992, approximately one month from Scott et al. (1994) The CO was absent from their data, but the signal-to-noise ratio was low and weak absorption could have been present. Harrison et al. (1993) concluded that CO emission from an accretion disc veiled the photospheric features of the RG. An alternative explanation was given by Scott et al. (1994): they concluded the outburst contaminated the secondary with carbon, which was then convected away, restoring the carbon abundance to its original value.

Scott et al. (1994) dismissed the Harrison et al. explanation because of the absence of CO emission in high signal-to-noise ratio data. The same conclusion can be reached from our data, which show only band absorption profiles consistent with a late-type star. Harrison et al. based their conclusion on the discovery of CO first overtone emission in the accretion discs around pre-main-sequence stars. However, CO first overtone emission has been detected in few eruptive variables: six classical novae (NQ Vul, V842 Cen, V705 Cas, V1419 Aql, V2274 Cyg and V2615 Oph), in which the CO formed in cool, neutral regions in the ejecta (Ferland et al. 1979; Hyland & McGregor 1989; Lynch et al. 1995; Evans et al. 1996; Rudy et al. 2003; Das, Banerjee & Ashok 2009) and the peculiar eruptive variable V838 Mon (Rushton et al. 2005). We do not therefore expect CO emission in RS Oph, as the temperature of the shocked gas is $\sim 10^6$ K (Evans et al. 2007a).

According to Scott et al. (1994), the CO bands deepen when the nova ejecta contaminate and sweep past the secondary. Drake et al. (2009) and Ness et al. (2009) argue that the C is overabundant in the nova ejecta from an analysis of *Chandra* X-ray data. Since the C-enriched ejecta would pollute the RG within hours of the outburst, and any carbon deposited in the atmosphere would quickly combine with oxygen to form CO, Scott et al. suggest that the CO bands deepen shortly after optical maximum. They then argue that the CO weakens, as convection reduces the carbon abundance to the pre-outburst value, which is reached after $\sim 10^2$ days. However, the CO absorption weakened and then deepened in our data, inconsistent with the behaviour predicted by Scott et al.. Therefore, contamination of the secondary alone cannot explain the evolution of the CO.

The weakening in our data of the CO absorption and the disappearance of the H^- opacity minimum peak imply a higher RG temperature in 2007. A possible explanation is that the WD heats the RG hemisphere facing the primary. As the star orbits the WD, varying fractions of the irradiated hemisphere of the RG are presented to the observer and the depths of the molecular bands change with phase Φ. The problem with this explanation is that the weakest CO is observed at $\Phi = 0.12$, when 26 per cent of the irradiated hemisphere is visible, and not at other phases, when similar or even larger fractions are visible. We would expect the CO absorption to be weakest when we see the largest fraction of the irradiated hemisphere and the effect of irradiation (and hence destruction of CO) is at its maximum.

Anupama & Mikołajewska (1999) monitored RS Oph in quiescence and observed variability in the absorption from the RG. From the $[TiO]_1$, $[TiO]_2$, [VO] and [Na] spectral indices (defined by Kenyon & Fernandez-Castro 1987), they found that features at shorter wavelengths imply an earlier spectral type than features at longer wavelengths (see also table 5 in Dobrzycka et al. 1996). They concluded that the variable blue continuum from the hot component veiled the absorption from the RG. This effect was noticed in other symbiotic stars by Kenyon & Fernandez-Castro (1987), who showed that the spectral indices are correlated with the visual brightness of the system. Although this explains variability of optical absorption features, it is unlikely to be responsible for the behaviour of the CO, as the contribution from the hot component is negligible at 2.3 μm. Furthermore, the CN bands, which are in the blue part of the spectrum, would show a significant and larger change, but this is not observed in our data.

The only alternative explanation for the behaviour of the CO is that the RG is intrinsically variable. Rosino, Bianchini & Rafanelli (1982) estimated as M2-III the spectral type of the RG. They had monitored RS Oph for 12 years after the 1967 outburst and noted that the secondary is 'perhaps slightly variable', although the variability they observed could be due to the blue continuum, as mentioned above.

More pertinent to the subject matter of this paper is the measurement by Kenyon (1988) of a 'CO index' ([CO] = [2.4]–[2.17], where [2.4] and [2.17] are narrow-band magnitudes in the region of the CO first overtone bandhead) in 1985–1986, in the aftermath of the 1985 eruption; Kenyon found the CO index to be variable. It is unfortunate that, apart from Scott et al. (1994) and Harrison et al. (1993), there has been no 1–2.5 μm spectroscopy of RS Oph in quiescence. The spectroscopic variability of the RG should be confirmed by regular IR monitoring, where the contribution from the hot component is negligible.

4.2 Dust

In this paper, we show that RS Oph exhibits an excess at >3 μm (see Fig. 6) due to emission from the dust already known to exist in the system. The dust is present in quiescence and survives the UV flash of the outburst. Evans et al. (2007b) suggest that the dust is largely confined to the binary plane and that this higher density material is effectively shielded from the eruption. Furthermore, if the dust temperature is $T_d = 500$ K, the dust is heated in outburst to only $T_d = 1250$ K, below the sublimation temperature, although the situation is marginal (see Evans et al. 2007b). This dust will then be present at the next eruption, provided it survives the passage of the shock.

The fitting analysis (see Section 3.2 and Table 1) seems to imply that the dust may not have survived, as the IR excess seems to have disappeared between 2006 September and 2007 June, only to develop again, shortly after. Fig. 1 shows that the 2007 spectra (showing no dust excess) were obtained during a small-amplitude rebrightening event in the visual light curve, while the earlier and later spectra (with the dust excess) were obtained when the visual magnitude was close to the quiescent value. Since the 2007 spectra show no IR excess, the rise in the *V*-band flux might be interpreted in terms of the dissipation of the dust and its subsequent decline to the formation of new dust in the cooling ejecta. However, this interpretation of the light curve is unlikely, as the optical depth in the visual due to the pre-outburst dust is only $\tau_V = 0.1$ (van Loon 2008). Furthermore, the temperature of the newly formed silicate dust would be close to the condensation temperature ($\simeq 1300$ K; Speck et al. 2000), much higher than the temperature we find after the redevelopment of the excess, ~ 500 K. Also, as discussed in Evans et al. (2007b), conditions are unlikely to be suitable for dust condensation in the ejecta. Moreover, as our data only go as far as 5 μm, it is in any case possible that an IR excess is still present in 2007, but at wavelengths longer than that covered by our data.

However, it is interesting that the disappearance of the IR excess shortward of 5 μm coincides almost exactly with a change in the 9.7 μm silicate feature in *Spitzer* spectra (Evans et al. 2007b): the narrower feature is present in 2007 April, ∼2 months before we see no excess. We will present a detailed discussion of the circumstellar dust in the RS Oph system in a separate paper.

5 SUMMARY

We have presented IR spectroscopy of the RN RS Oph on eight occasions after the most recent outburst in 2006 February. The spectra contain emission lines from the outburst superimposed on the spectrum of the RG in the system. We have fitted synthetic spectra to the data to determine the effective temperature of the RG and dusty envelope. Although the parameters on all observation dates are consistent within the uncertainties, the spectral features from the RG are variable. This variability cannot be explained by contamination of the RG, irradiation or veiling from the hot component. The most likely explanation is that the RG is intrinsically variable. This variability should be confirmed by monitoring of RS Oph in the IR, where the RG dominates the continuum.

The spectra show an IR excess at $>3\ \mu$m due to emission from the circumstellar dust detected in earlier studies. The excess is present in our 2006 and 2008 data, but absent in our 2007 data. However, it is possible the excess is present in 2007, but at longer wavelengths than are covered by our data.

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